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Differences on Results from Steady-state and Time-dependent Wall/roof Heat Transfer Models in Mexican Climates

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Abstract

Mexican regulations aiming to reduce the air conditioning energy consumption in buildings use methods based on the steady-state heat transfer model. Thus, they take into account the thermal resistance of the envelope elements, but do not consider their thermal storage capacity (or heat capacity). This model is useful to estimate the needs of heating in winter for countries in the temperate or polar areas where the temperature oscillation during one day is small and solar radiation is low. When the temperature oscillation during one day is large and the solar radiation is high, like in Mexican climates, the wall/roof thermal storage capacity is very important. In these cases, a method based on the time-dependent heat transfer model must be used. In this work, the results of the wall/roof heat transfer from the steady-state model are compared with the results from the time-dependent model. Four roof constructive systems have been considered, in three different Mexican cities. Their thermal performance has been analyzed for air-conditioned buildings and for non-air-conditioned ones. It is demonstrated that the differences on the results from the steady-state model and the time-dependent model can be greater than 80% for air-conditioned buildings, and greater than 800% for the non-air-conditioned case. These results show the need to change Mexican regulations incorporating methods for evaluating the envelope walls/roofs heat transfer based on the time-dependent model.

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Keywords: heat transfer; time-dependent;steady-state; building envelope;

1. Introduction

In Mexico approximately 30% of total energy consumption corresponds to the residential, commercial sectors and services. It is estimated that in hot climates, about 35% of this energy is used for the air-

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conditioning of the buildings [1]. The bioclimatic design of the new buildings can impinge significantly on energy savings in Mexico. A suitable bioclimatic design minimizes, or cancels, the requirements of energy for hygrothermal and air-quality conditioning of the building interior. Within the key components in the bioclimatic design is the use of materials for the envelope walls and roofs, with physical properties appropriate to the climate.

Since in those countries that have been most studied the effect of materials of the envelope walls/roofs, the main problem for thermal conditioning is during the winter, where the daily external temperature variation is small compared with the difference between the outdoor temperature and the air-conditioned temperature and solar heat gains do not vary significantly during 24 hours, the methods to evaluate the envelope materials based on an analysis of heat transfer in steady-state give satisfactory results. For this reason and because of the simplicity of these methods, these methods are used for the development of standards or regulations of construction in these countries. But in Mexico, the main problem of thermal conditioning is in warm climates. In these climates, solar radiation is significant and the daily temperature swing is important [2], conditions in which the methods based on an analysis of the steady-state heat transfer are not applicable [3]. Despite this, in Mexico the official standard for energy efficiency in buildings the NOM-008-ENER-2001 [4] and the NOM-020-ENER-2011 [5], for non-residential and residential building envelopes respectively, are based on analysis of heat transfer in steady-state. Also the non-official standard NMX460 [6] and the new evaluation system for housing of the Mexican federal institute for worker's housing (INFONAVIT from *Instituto del Fondo Nacional de la Vivienda para los Trabajadores*) [7] are based on the steady-state model.

The main objective of this paper is to demonstrate the importance of the analysis of time-dependent heat transfer in Mexican climates. Results of the wall/roof heat transfer from the steady-state model are compared with the results from the time-dependent model. Four roof constructive systems are considered, in three different Mexican cities. Their thermal performance is analyzed for air-conditioned buildings and for non-air-conditioned ones.

2. Physical model

To evaluate the thermal behavior of an envelope element, wall or roof, of total thickness L made of N homogeneous layers a one-dimensional model is a good approximation. The effects of convection and radiation on the surfaces of the element are modeled using film heat transfer coefficients, *ho* for outdoor surface and *hi* for the indoor. The physical model is outlined in Fig. 1, for the particular case of an element made up of two layers (N=2).

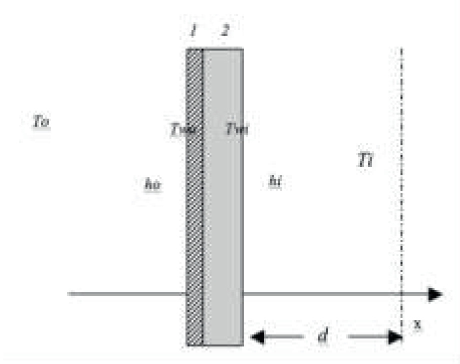

Fig. 1. Physical model of heat transfer through an element of the envelope. Case of an element made up of two layers.

Nomenclature

A	the solar absorptivity of the outdoor surface
α_j	thermal diffusivity of the material of the *j-th* layer
c_a	specific heat of air
C_j	thermal storage capacity or heat capacity of the material of the *j-th* layer
c_j	specific heat of the material of the *j-th* layer
d	distance from the indoor surface where there is no heat transfer
hi	indoor surface heat transfer coefficient
ho	outdoor surface heat transfer coefficient
k_j	thermal conductivity of the *j-th* layer
L	total thickness
L_j	thickness of the *j-th* layer
N	number of homogeneous layers
q	flow of heat per unit area
R	total thermal resistance
RF	infrared radiation factor
ρ_a	density of air
ρ_j	density of the material of the *j-th* layer
T	temperature
t	time
Ti	indoor air temperature
To	outdoor air temperature
Tsa	sol-air temperature
Twi	temperature of the indoor surface
Two	temperature of the outdoor surface
x	spatial coordinate transverse to the wall/roof

In the model, combined effects of the incident solar radiation, *I*, the outdoor air temperature, *To*, and the infrared radiation to the sky, on the wall/roof are taken into account through an equivalent temperature called sol-air temperature, *Tsa*,

$$Tsa = To + \frac{AI}{ho} + RF, \tag{1}$$

where *A* is the solar absorptivity of the outdoor surface, and *RF* the infrared radiation factor [7].

2.1. Steady-state heat transfer model

The equation of steady-state (time-independent) heat transfer by conduction in one-dimension for the *j-th* layer of thickness L_j of a wall/roof made by homogeneous layers is [8]

$$\frac{\partial^2 T}{\partial x^2} = 0. \tag{2}$$

Where, k_j is the thermal conductivity of the *j-th* layer and x is the spatial coordinate transverse to the wall/roof. The total thickness of the element is given by the sum of the thicknesses of the N layers. By energy conservation, the following relationship must be met at the joints of the layers

$$-k_j \left.\frac{dT}{dx}\right|_{j,j+1} = -k_{j+1} \left.\frac{dT}{dx}\right|_{j,j+1} \tag{3}$$

and at the outdoor and indoor surfaces

$$-k \left.\frac{dT}{dx}\right|_{wo} = ho(Tsa - Two) \qquad -k \left.\frac{dT}{dx}\right|_{wi} = hi(Twi - Ti). \tag{4}$$

Two is the temperature of the outdoor surface of the element, Twi is the temperature of the indoor surface, and Ti is the indoor air temperature, as shown in Fig. 1. The Fourier law provides the heat flow per unit area, q,

$$q = \frac{Tsa - Two}{1/ho} = \frac{Two - T_{1,2}}{L_1/k_1} = \ldots = \frac{T_{N-1,N} - Two}{L_N/k_N} = \frac{Twi - Ti}{1/hi}. \tag{5}$$

Using the concept of total thermal resistance R (also known as total R-value), the flow of heat per unit area, q, can be expressed as

$$q = \frac{Tsa - Ti}{R}, \tag{6}$$

where R is given by the sum of the resistances of the outdoor and indoor surfaces, $1/ho$ and $1/hi$, respectively, plus the conductive resistances of the N layers,

$$R = \frac{1}{ho} + \frac{L_1}{k_1} + \ldots + \frac{L_j}{k_j} + \ldots + \frac{L_N}{k_N} + \frac{1}{hi}. \tag{7}$$

Therefore, in steady-state, the only property of the wall/roof that determines the heat transfer is R, the greater R, the better its thermal performance.

2.2. Time-dependent heat transfer model

The equation of time-dependent heat transfer by conduction in one-dimension for the *j-th* layer of thickness L_j of a wall/roof made by homogeneous layers is [8]

$$\frac{\partial T}{\partial t} - \alpha_j \frac{\partial^2 T}{\partial x^2} = 0. \tag{8}$$

This equation describes the variation of the temperature inside the *j-th* layer, T, as function of time t. The coefficient α_j is the thermal diffusivity of the material of the *j-th* layer and is defined as the ratio of the thermal conductivity k_j and thermal storage capacity or heat capacity or thermal mass, per unit of volume, of the material $Cj = \rho_j c_j$

$$\alpha_j = \frac{k_j}{C_j} = \frac{k_j}{\rho_j c_j}, \tag{9}$$

where, ρ_j is the density and c_j is the specific heat. By conservation of energy at the joints of the layers and outdoor and indoor surfaces, equations (3) and (4) must be met. In this model, Tsa is a function of time.

2.3. Consideration for air-conditioned buildings

For air-conditioned buildings, the indoor air temperature, *Ti,* is considered constant and equal to the neutrality temperature given by [9] that is based on the monthly average of the outdoor air temperature.

2.4. Consideration for non-air-conditioned buildings

For non-air-conditioned buildings, *Ti* is calculated from the heat transferred through the wall/roof

$$q = h_i(Twi - Ti) = d\rho_a c_a\left(\frac{\partial Ti}{\partial t}\right) \tag{10}$$

where ρ_a and c_a are the density and the specific heat of air. It is assumed there is a distance *d* from the interior surface where there is no heat transfer, *i.e.* an adiabatic condition.

3. Roof constructive systems

To compare the thermal performance of envelope elements given by the steady-state and time-dependent models, four roof constructive systems are analyzed. The four roofs have the same total thickness (10cm), the first one is made of a layer of high density concrete (HDC), the second is made of a layer of expanded polystyrene foam (EPS), the third and fourth are made of two layers, one of HDC with 8cm of thickness and other of 2cm of EPS. In the third roof, the EPS layer is at the outdoor side, and in the fourth system, the EPS layer is at the indoor side. The roof systems characteristics are described in Table 1 and the thermal properties of the materials used [10] are presented in Table 2. For the four roofs *A*=0.7.

Table 1. Description of the four roof constructive systems (C.S.). The layers are presented from outdoor to indoor layers, in brackets is the layer thickness. HDC is high density concrete, EPS is expanded polystyrene foam.

C.S.	Layers from outdoor to indoor (thickness)
C.S. 1	HDC (10cm)
C.S. 2	EPS (10cm)
C.S. 3	EPS (2cm) + HDC (8cm)
C.S. 4	HDC (8cm) + EPS (2cm)

Table 2. Thermal properties of the materials used in the constructive systems. HDC is high density concrete, EPS is expanded polystyrene foam.

Material	k (W/(mK))	ρ (kg/m^3)	c (J/(kgK))
EPS	0.04	15	1400
HDC	2.00	2400	1000

4. Comparison of steady-state and time-dependent models results

The four roof constructive systems are considered in three different Mexican cities. Their thermal performance is analyzed during the typical day of a month for air-conditioned buildings and for non-air-conditioned ones. The selected cities and months are Hermosillo-June (hot month in an extreme-hot climate), Temixco-May (hot month in a sub-humid hot climate), and Toluca-January (mild cold month in a cold climate). To evaluate the thermal performance with the steady-state model using the time-dependent *Tsa*, a quasi-steady approach has been used. For each step-time (1/6s) the steady-state equations are considered, calculus is made in an excel-spreadsheet. For the evaluation of the thermal performance with the time-dependence model, the simulation tool Ener-Habitat [11-12] has been used. For both models, *ho* and *hi* values are taken from the NOM-008-ENER-2001 [4] and the NOM-020-ENER-2011 [5] norms, *i.e.* ho=13W/m^{2}K and hi=6.6W/m2K. Also the values of d, ρ_a, and c_a are the same in both models (d=2.5m, ρ_a=1.1797kg/m^3, and c_a=1005.45J/kg^{o}C).

4.1. Results for air-conditioned buildings

The thermal parameter used to compare models results for air-conditioned buildings is the total thermal load (heating plus cooling thermal loads). As an example, Fig. 2 shows the thermal load calculated from both models for the typical day of May in Temixco: steady-state model (red) and time-dependent model (green), for the four constructive systems (C.S.). Steady-state model orders these constructive systems, from best to worst as 2, 3=4, and 1, the time-dependent model gives similar order, but evaluates C.S. 3 as slightly better than S.C. 4.

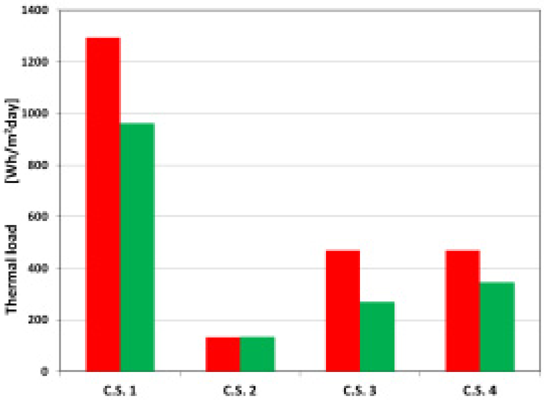

Fig. 2. Thermal load for the typical day of May in Temixco for each constructive system, calculated from the steady-state model (red) and from the time-dependent model (green).

Table 3 summarizes the percentage differences of the thermal load calculated with the steady-state model and with the time-dependent model. It can be observed that for the C.S. 2 both models give almost the same results, this is due to the fact that this C.S. is made of a material with a low heat capacity, but for others C.S., with higher heat capacities, the differences become important. The greatest differences are for C.S. 3, up to 83%. In general, the state-state model overvalues the thermal load for systems with heat capacity (or thermal mass). These results are in accordance with Ref. [13].

Table 3. Percentage differences of the thermal load calculated with the steady-state model and with the time-dependent model for the four roof constructive systems (C.S.).

C.S.	Hermosillo-June	Temixco-May	Toluca-January
C.S. 1	25	34	38
C.S. 2	0	-1	-5
C.S. 3	43	74	83
C.S. 4	24	35	40

4.2. Results for non-air-conditioned buildings

Fig. 3 shows a qualitative comparison of the indoor air temperature given by the steady-state model and by the time-dependent model for the typical day of May in Temixco for the four C.S. It can be observed that the greatest differences are for the S.C. 4. and the smaller differences are for the S.C. 2.

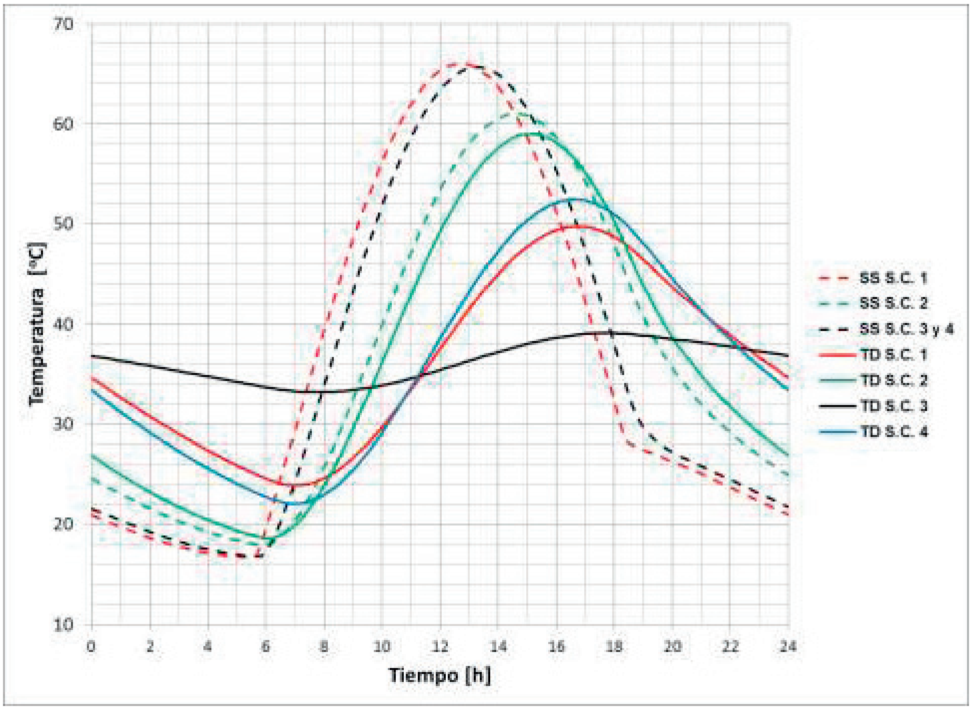

Fig. 3.Indoor air temperature given by the steady-state (SS dot lines) model and by the time-dependent (TD continuous lines) model for the typical day of May in Temixco for the four C.S.

For a quantitative comparison in non-air conditioned buildings, the thermal parameter used is the transmitted energy [14]. As an example, Fig. 4 shows the transmitted energy calculated from both models for the typical day of May in Temixco: steady-state model (red) and time-dependent model (green), for the four constructive systems (C.S.). Steady-state model orders these C.S. from best to worst as 2, 3=4, and 1. The time-dependent model gives very different order, 3, 1, 4, 2. Note that the order given by each model for air-conditioned and non-air-conditioned buildings is different. The different behavior of C.S depending on air-conditioned or non-air-conditioned conditions given by the time-dependent model has been reported previously [15].

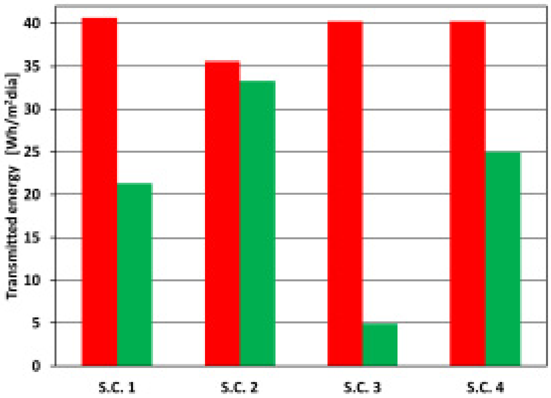

Fig. 4. Transmitted energy for the typical day of May in Temixco for each constructive system, calculated from the steady-state model (red) and from the time-dependent model (green).

The percentage differences of the transmitted energy calculated with the steady-state model and with the time-dependent model are presented in Table 4. Also for non-air-conditioned condition, both models give similar results for the C.S. 2. For others C.S., with higher heat capacities, the differences are very important. The greatest differences are for C.S. 3, up to 824%. For all the analyzed cases, the steady-state model overvalues the transmitted energy. For all the cities, the steady-state and the time-dependent models give different best to worst order of the constructive systems.

Table 4. Percentage differences of the transmitted energy calculated with the steady-state model and with the time-dependent model for the four roof constructive systems (C.S.).

C.S.	Hermosillo-June	Temixco-May	Toluca-January
C.S. 1	85	91	108
C.S. 2	6	7	8
C.S. 3	697	724	824
C.S. 4	57	61	74

5. Conclusions

Results of the wall/roof heat transfer from the steady-state model are compared with the results from the time-dependent model. Four roof constructive systems are considered, in three different Mexican cities. Their thermal performance is analyzed for the typical day of a month, for air-conditioned buildings and for non-air-conditioned ones.

For the analyzed cases, for the air-conditioned condition, the percentage differences of the thermal load calculated with the steady-state model and with the time-dependent model is up to 83%. The state-state model overvalues the thermal load for constructive systems with heat capacity (or thermal mass). The use of the steady-model to calculate the thermal-load in buildings with walls/roofs with thermal storage capacity or heat capacity can result in oversizing of air-conditioning-systems and plants.

For the non-air-conditioned condition, the percentage differences of the transmitted energy calculated with the steady-state model and with the time-dependent model are up to 824%. For all the analyzed cases, the steady-state model overvalues the transmitted energy, but the difference is bigger for constructive systems with high heat capacity.

This research demonstrates the importance of the analysis of time-dependent heat transfer in Mexican climates and the condition of the building, with or without air-conditioning. This research points out the urgency to modify Mexican regulations and the evaluation system of the INFONAVIT.

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